

**Multidisciplinary Design Optimization
Techniques:
Implications and Opportunities for Fluid
Dynamics Research**

**30th AIAA Fluid Dynamics Conference
Norfolk, VA
June 28 - July 1, 1999**

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<http://fmad-www.larc.nasa.gov/mdob/MDOB/>

Outline

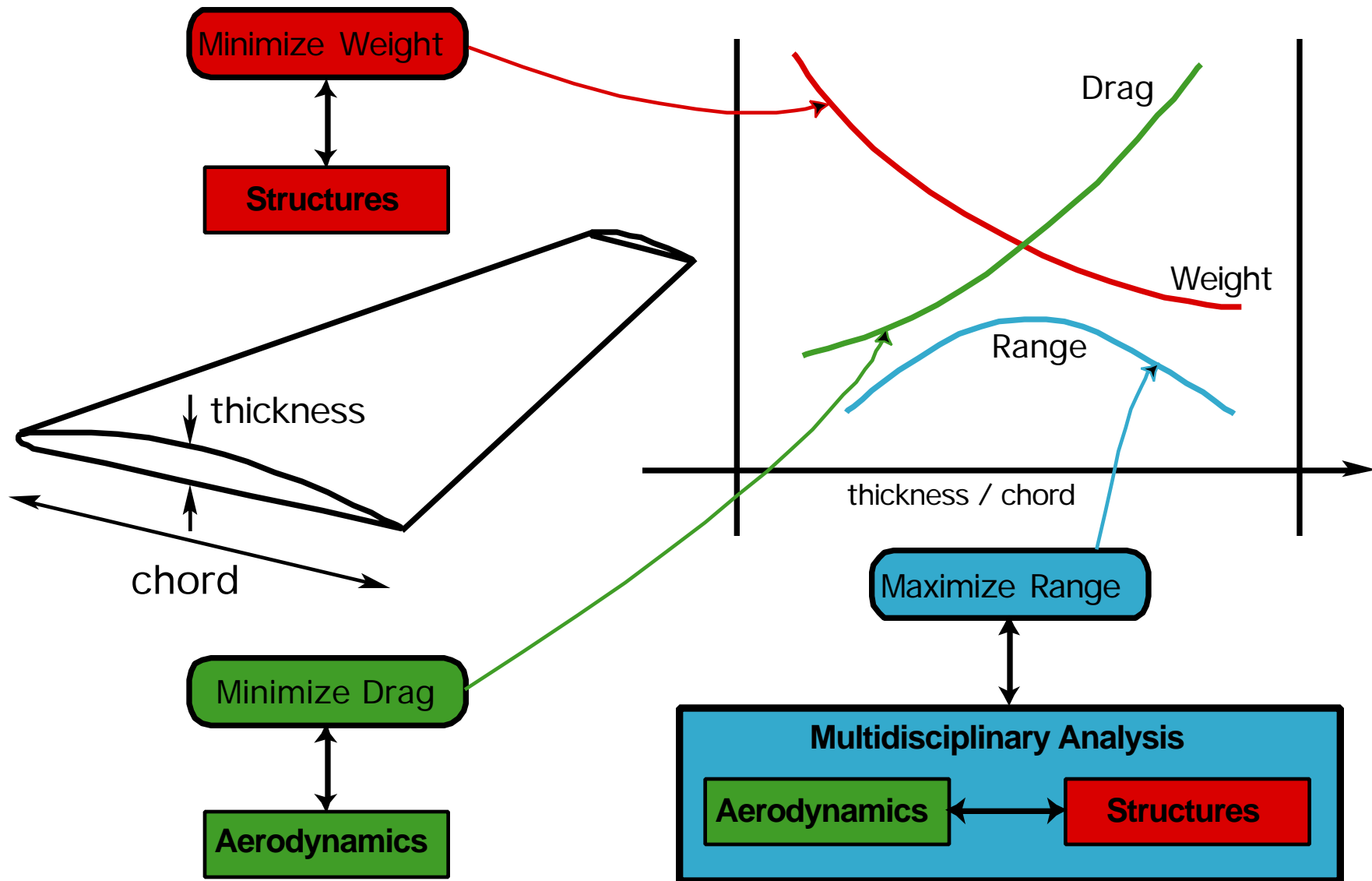
- **MDO Background**
- **Two MDO Applications**
- **Overview of MDO Technologies**
- **Implications and Opportunities for Fluid Dynamics**

MDO Definition

Multidisciplinary Design Optimization (MDO) is a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena (and system components)

Multidisciplinary Synergy

Wing Optimization Example



Short History of MDO & Related Aerodynamics Developments

- **1970s**
 - Initial developments in structures & aerodynamics optimization
- **1980s**
 - Numerous MDO developments centered on structures discipline
 - MA&O Symposium inaugurated (1984)
 - Sobieski issues call for aerodynamics sensitivity analysis (1986)
 - AIAA MDO TC established (1989)
- **1990s**
 - Aerodynamics sensitivity analysis developed
 - Aerodynamics optimization techniques developed
 - Interdepartmental MDO research groups established

General MDO References

- **“Current State of the Art in Multidisciplinary Design Optimization,” AIAA MDO Technical Committee, 1991**
- **Sobieszczanski-Sobieski, J., and Haftka, R.T., "Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments," *Structural Optimization*, Vol. 14, No. 1, 1997, pp. 1–23**
- ***Proceedings of the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, St. Louis, MO, 1998**
- **Giesing, J., and Barthelemy, J.-F. M., "Summary of Industry MDO Applications and Needs," AIAA Paper 98-4737, 1998**
- **Livne, E., ed., *Journal of Aircraft*, Vol. 36, No. 1, 1999 (28 articles on MDO)**

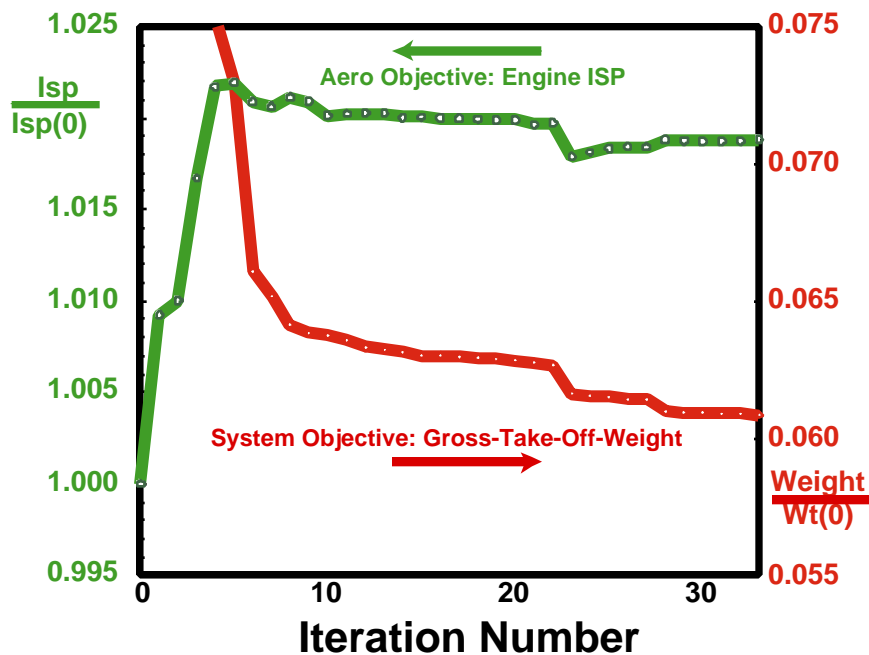
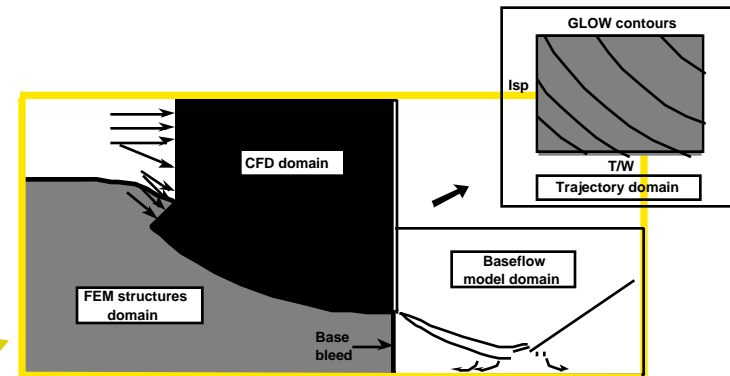
X-33 with Aerospike Engine



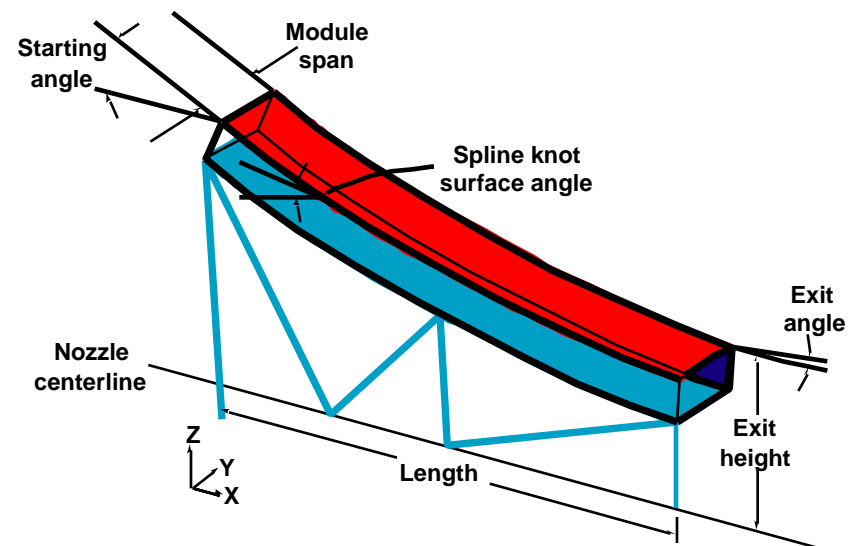
MDO Applied to an Aerospike Nozzle



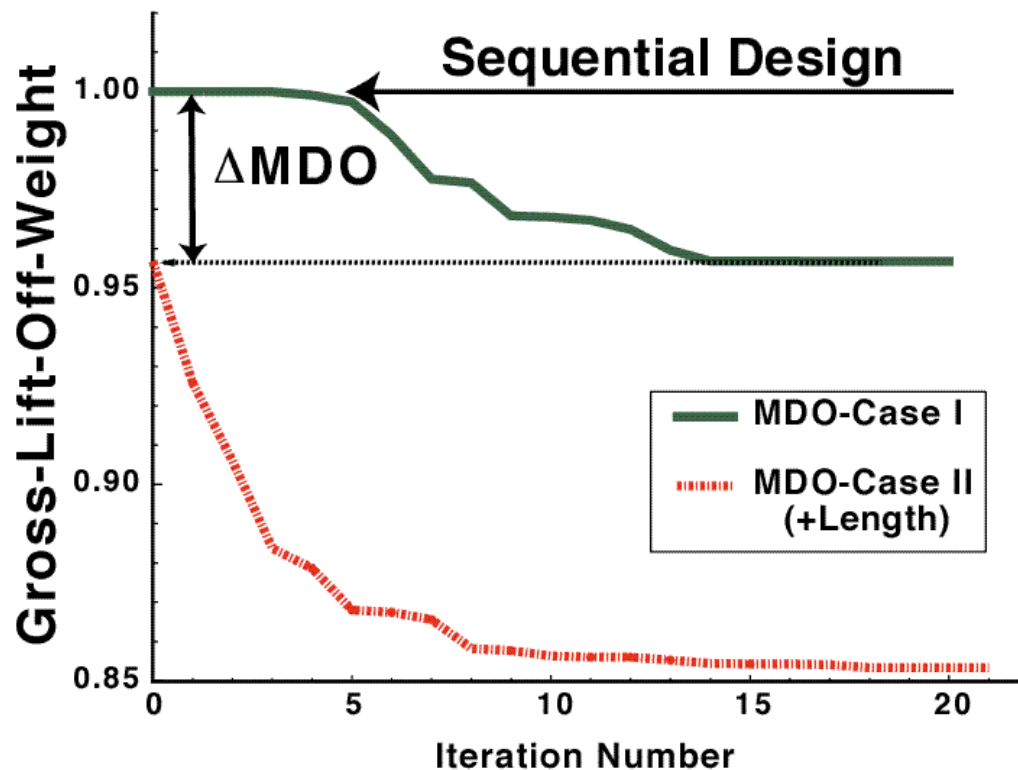
Nozzle Modeled by a 2-D Section



Nozzle Geometry Design Variables



MDO Impact on Aerospike Nozzle Model Problem

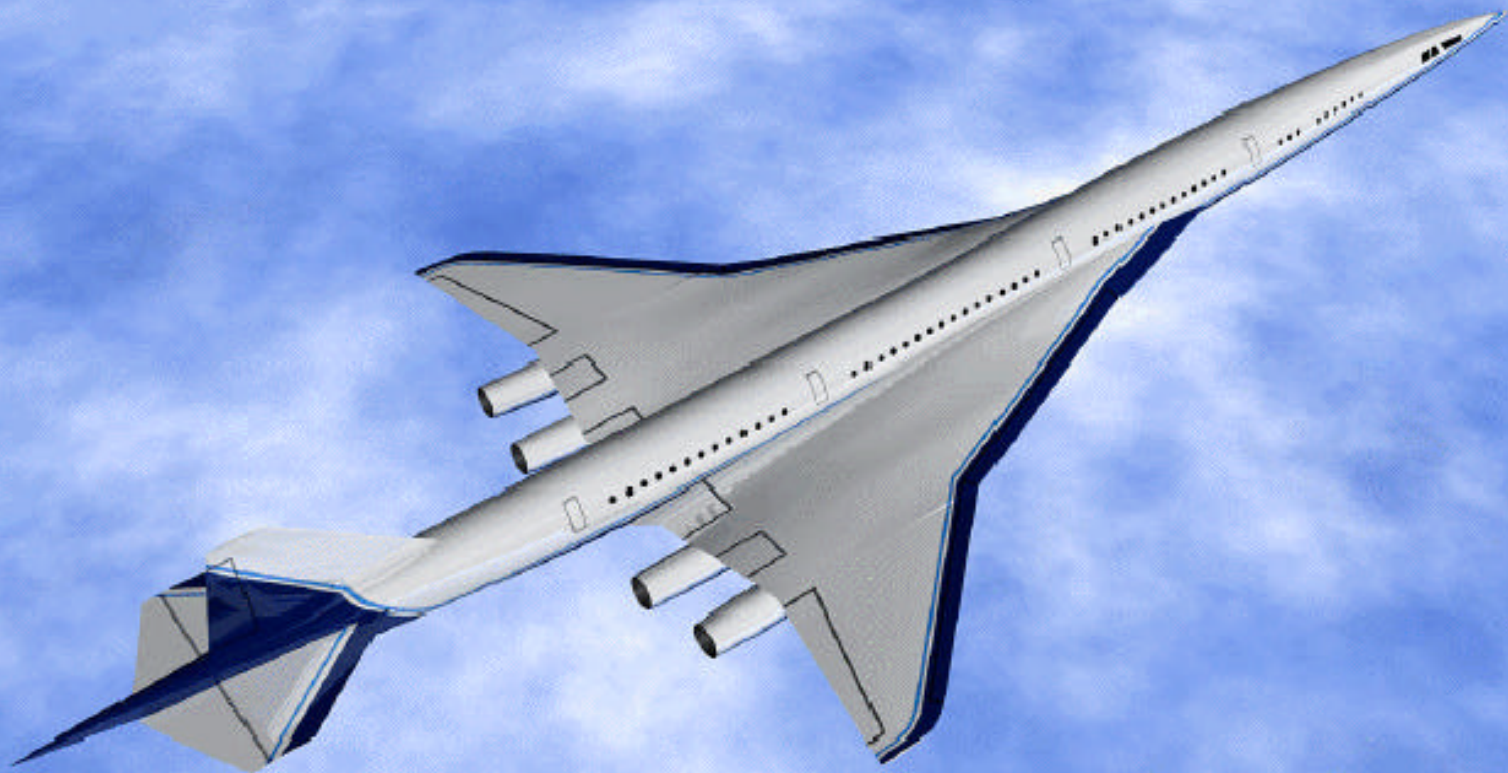


- **Sequential Design**
 - optimize the aero shape for maximum I_{sp}
 - then optimize the structure for minimum GLOW
- **MDO Design**
 - optimize the aero & structures together for minimum GLOW
 - produces 4% reduction in GLOW

Aerospike Nozzle Application

- **Joint development by LaRC MDO Branch & Rocketdyne**
- **Each site did a complete implementation with 2-3 engineers over 4 months**
- **Same codes used at both sites except for the structures discipline (because of existing FEM code licenses)**
- **The interdisciplinary analysis coupling was very weak because of the very stiff structure (negligible structural displacements due to aero loads)**
- **This was a technology development effort and was not used on the X-33 for the actual engine design**

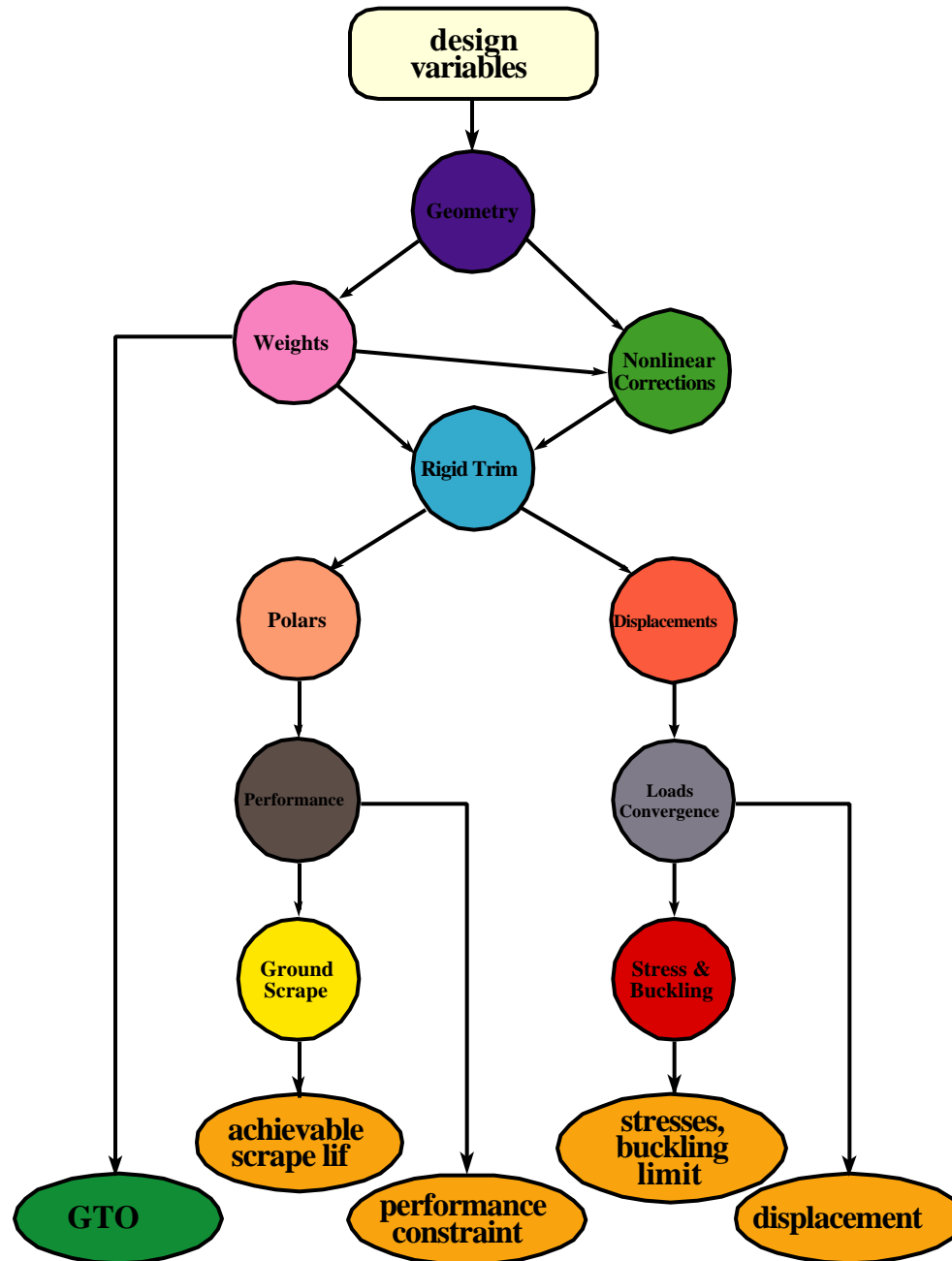
High Speed Civil Transport



HSCT Applications

Application	HSCT 2 (1994)	HSCT 3 (1997)	HSCT 4 (1999)
Design Variables	5	7	271
Constraints	6	6	31868
Major Codes Aerodynamics Structures Performance Propulsion	WINGDES ELAPS Range equation Engine deck	ISAAC COMET Range equation Engine deck	CFL3D, USSAERO GENESIS FLOPS Engine deck
Analysis Processes	10	20	70
Analysis Control Major loops Load conditions Mission conditions Processes (with loops) Total time	Weight Conv., Trim 2 1 O(10) O (minutes)	Weight Conv., Trim, Aeroelastic 2 1 O (100) O (1 hour)	Aeroelastic, Trim 7 10 O (1000) O (8 hours)
Optimization Cycle Total time/cycle	O (10 minutes)	O (3 hours)	O (3 days)

HSCT 4 Analysis



HSCT 4 Application

- **The interdisciplinary coupling was moderate**
 - aircraft has significant flexibility
 - interdisciplinary loops took as many as 3–10 iterations to converge
- **Founded on past HSCT MDO applications at LaRC dating back to HiSAIR Pathfinder (1989-94)**
- **Took ~10 engineers (Civil Servants & Contractors) over 2 years to define, assemble & debug the analysis portion**
- **The requirements document and software configuration management plan are both over 100 pages**

MDO Conceptual Elements

Giesing & Barthelemy (1998)

<i>Information Management and Processing</i>	<i>Analysis Capabilities and Approximations</i>	<i>Design Formulations and Solutions</i>	<i>Management and Cultural Implementation</i>
<ul style="list-style-type: none"> • MDO Framework and Architecture • Databases, Data Flow, and Standards • Computing Requirements • Design Space Visualization 	<ul style="list-style-type: none"> • Analysis and Sensitivity Capability • Parametric Geometric Modeling • Approximation and Correction Processes • Breadth vs. Depth Requirements • Effective Inclusion of High-Fidelity Analyses/Tests 	<ul style="list-style-type: none"> • Design Problem Objectives • Design Problem Decomposition and Organization • Optimization Procedures and Issues 	<ul style="list-style-type: none"> • Organizational Structure • MDO Operation in IPD Teams • Acceptance, Validation, Cost & Benefits • Training

Information Management & Processing

- **MDO does not purport to furnish a push-button design capability**
- **MDO seeks to provide the human designer with improved tools for achieving better designs by**
 - **Automating routine tasks**
 - **Furnishing useful information on interdisciplinary trades**
 - **Conducting design space searches**

MDO Framework & Architecture

Make or Buy?

- **Most of the human labor in implementing an MDO application (once it's defined) consists of**
 - **Preparing analysis codes for use in an MDO application**
 - **Linking the codes together in the proper control sequence**
- **There are many research activities and several commercial frameworks for this purpose**
- **No framework meets all the requirements for a high-end application such as HSCT 4**
- **Commercial frameworks are developing rapidly and some are already suitable for simpler applications**
- **Our advice to groups contemplating a framework for MDO applications is to buy not make**

Databases, Data Flow, and Standards

- **Problem definition for MDO applications is an essential, but time-consuming, process**
- **The HSCT 4 detailed problem definition takes over 100 pages**
- **This entailed considerable resistance from many of the engineers on the team and took over a year to develop**
- **Nevertheless, experience indicates that if the problem definition is not laid out in some detail at the beginning**
 - **the project may fail completely**
 - **the project will certainly take longer**

Analysis Capabilities and Approximations

- **Traditional analysis uses the one-of-a-kind analysis paradigm for high-fidelity tools**
- **MDO applications require broader capabilities in the analysis tools and judicious use of approximations**

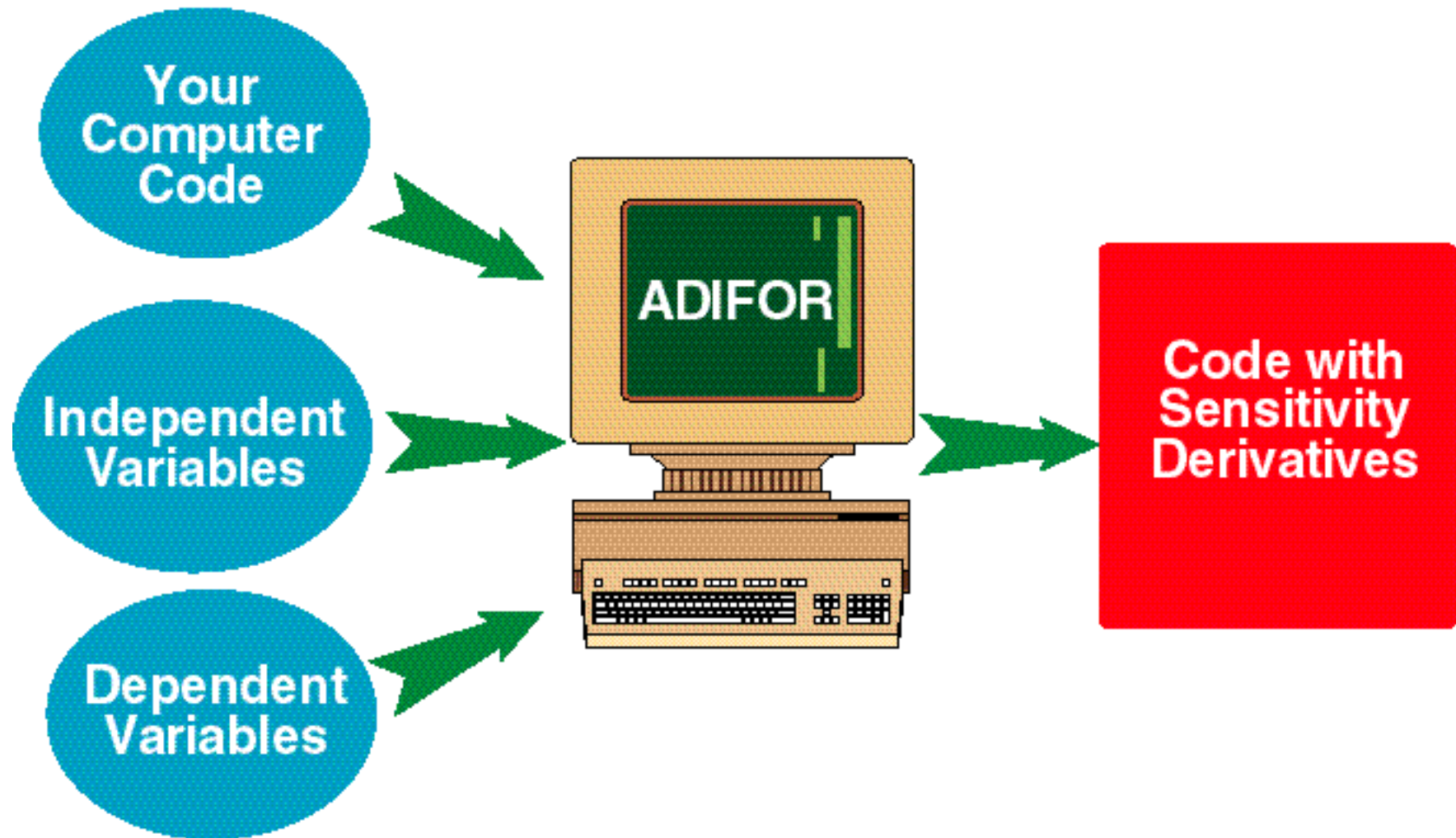
Analysis and Sensitivity Capability

- **From an MDO perspective, each disciplinary analysis code should be**
 - **Robust**
 - **Automated**
 - **Computationally efficient**
 - **Well documented**
 - **Equipped with accurate, efficient sensitivity analysis**
 - **Furnish error estimates**
- **The typical disciplinary codes that are used now in MDO applications have had to be enhanced/repared by the MDOers prior to use**

Sensitivity Analysis Approaches

- **Finite Differences**
 - seemingly effortless, but with uncertainty about step-size
 - inefficient in CPU time, but efficient in memory
- **Hand-Coded**
 - laborious & error prone (~1 year for a laminar NS code)
 - accurate & efficient in CPU time and in memory
- **Automatic Differentiation**
 - utilizes pre-processor (~1 week for a turbulent NS code)
 - accurate & moderately efficient
- **Complex Variables**
 - just change variables from real to complex (~1 week)
 - accurate & moderately efficient

ADIFOR Process



Automatic Differentiation Tools

- **Developed at Argonne National Laboratory (Bischof, et. al.) and Rice University (Carle, et. al.) with NASA LaRC, DOE, and NSF funding**
- **ADIFOR 2.0 (1995) received the Wilkinson Prize for numerical software**
- **New capabilities in ADIFOR 3.0 (to be released in late 1999)**
 - **Adjoint code via the ADJIFOR (reverse mode) tool**
 - **Hessian tool for second derivatives**
- **ADIC tool for C and C++ code**

ADIFOR CFD Application

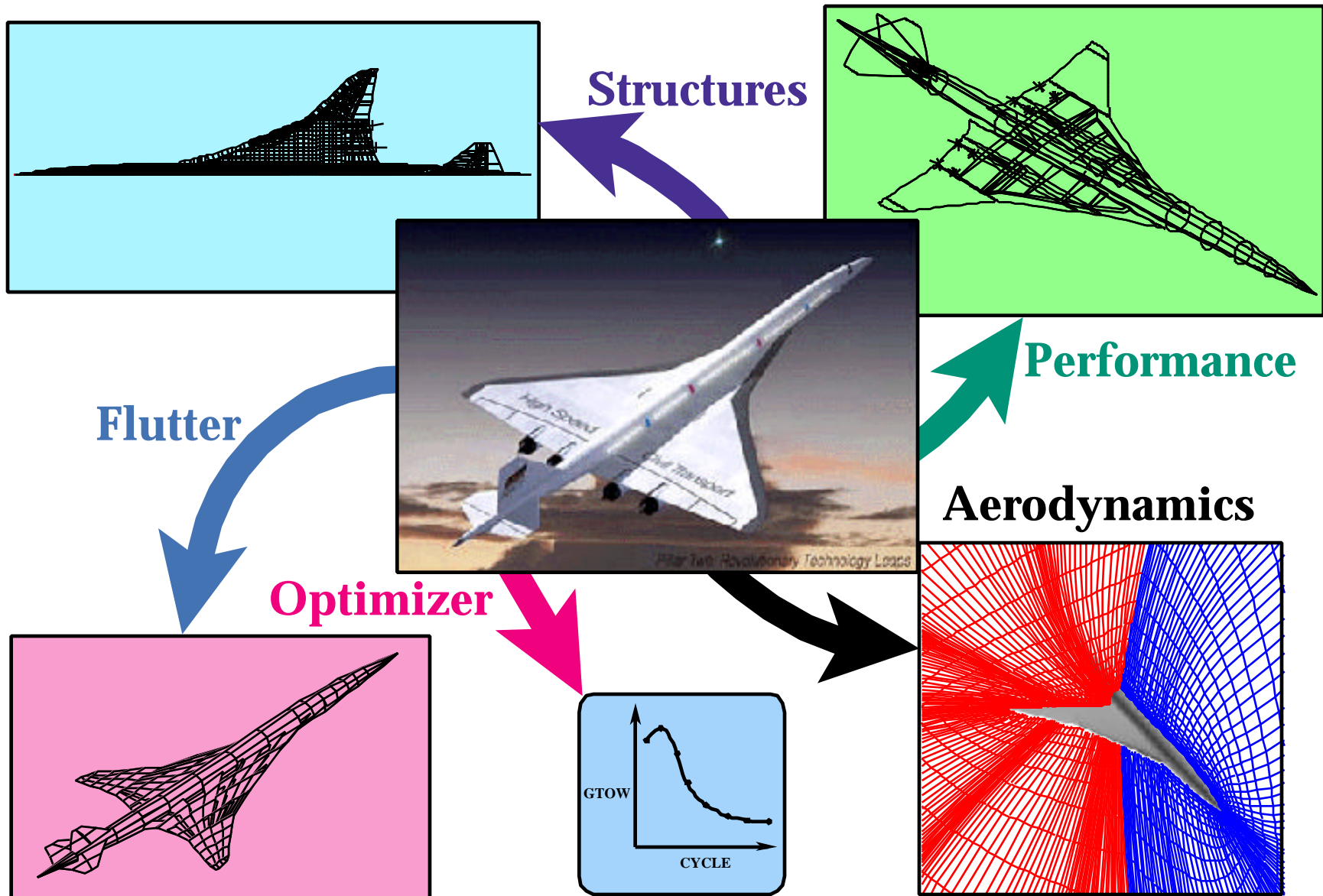
High Speed Civil Transport Shape Optimization

- **Boeing, Long Beach has been a pilot user of ADIFOR 3.0, with its adjoint capability**
- **HST shape optimizations have been performed using both Euler and turbulent Navier-Stokes capabilities of CFL3D with an automated adjoint**
 - **400 design variables**
 - **55 constraints**
 - **400,000 - 1,500,000 grid points**
- **Computations performed on 72 processors of the NAS Origin 2000**

Parametric Geometry Modeling

- **Parametric modeling (in terms of design variables) is necessary for optimization**
- **Parameterization must be consistent across the disciplines**

Geometry Models for a High Speed Civil Transport



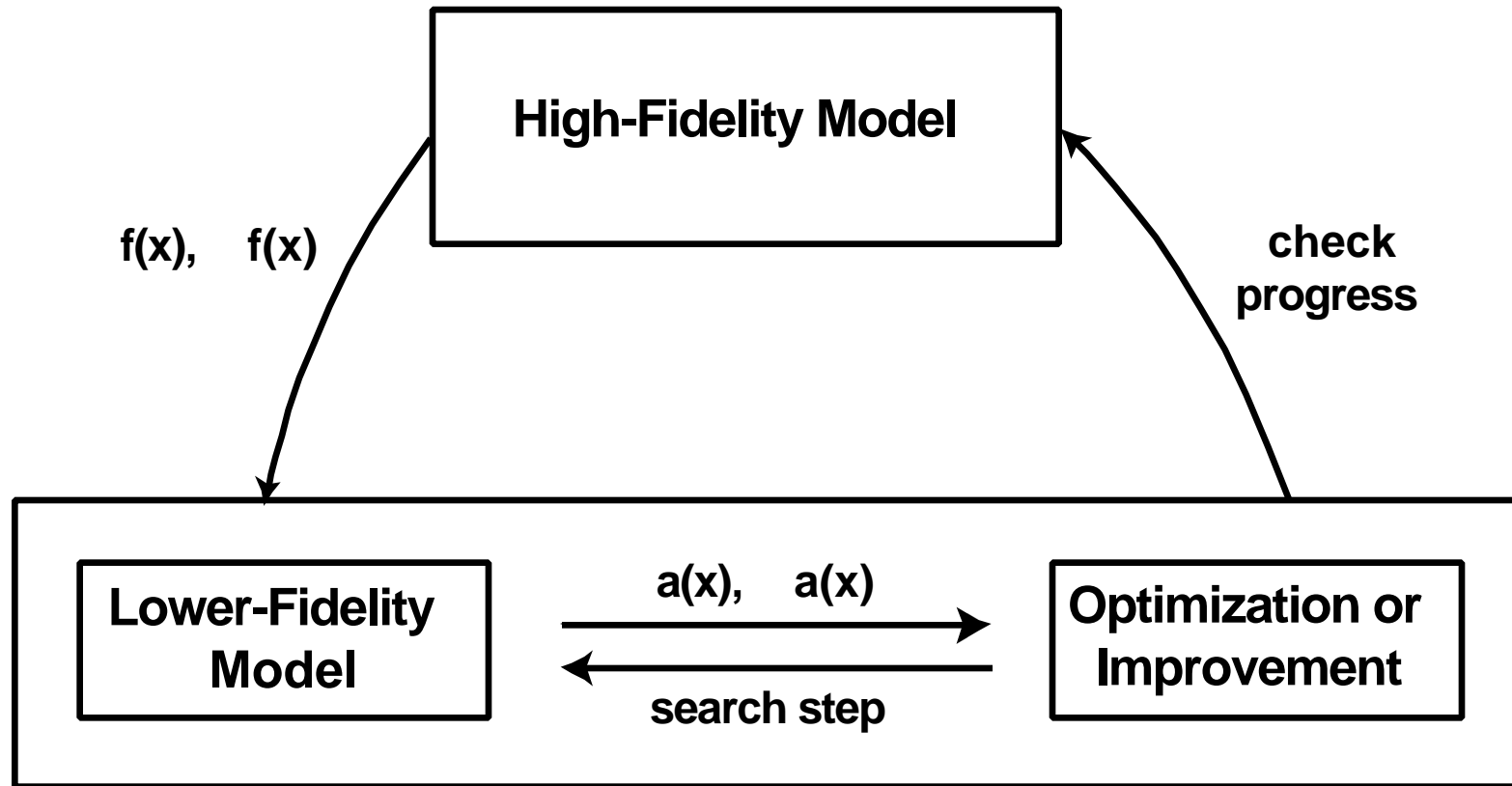
Approximation & Correction Processes

- **These are the keys to using the latest, high-fidelity codes in MDO applications because the lengthy run times of high-fidelity codes, especially CFD, restrict their direct use**
- **Approximation techniques include**
 - **response surfaces**
 - **design of experiments**
 - **neural networks**
 - **kriging**
 - **variable-fidelity approximations**

Approximation Management Framework

$f(x)$ - high fidelity, expensive model, e.g. *Navier-Stokes CFD*

$a(x)$ - lower fidelity or accuracy models of the same physical process, e.g. *panel method*



Result: Systematic use of inexpensive models in the repetitive process with only occasional recourse to expensive models yields convergence to critical points of expensive models without the conventional expense.

Design Formulations and Solutions

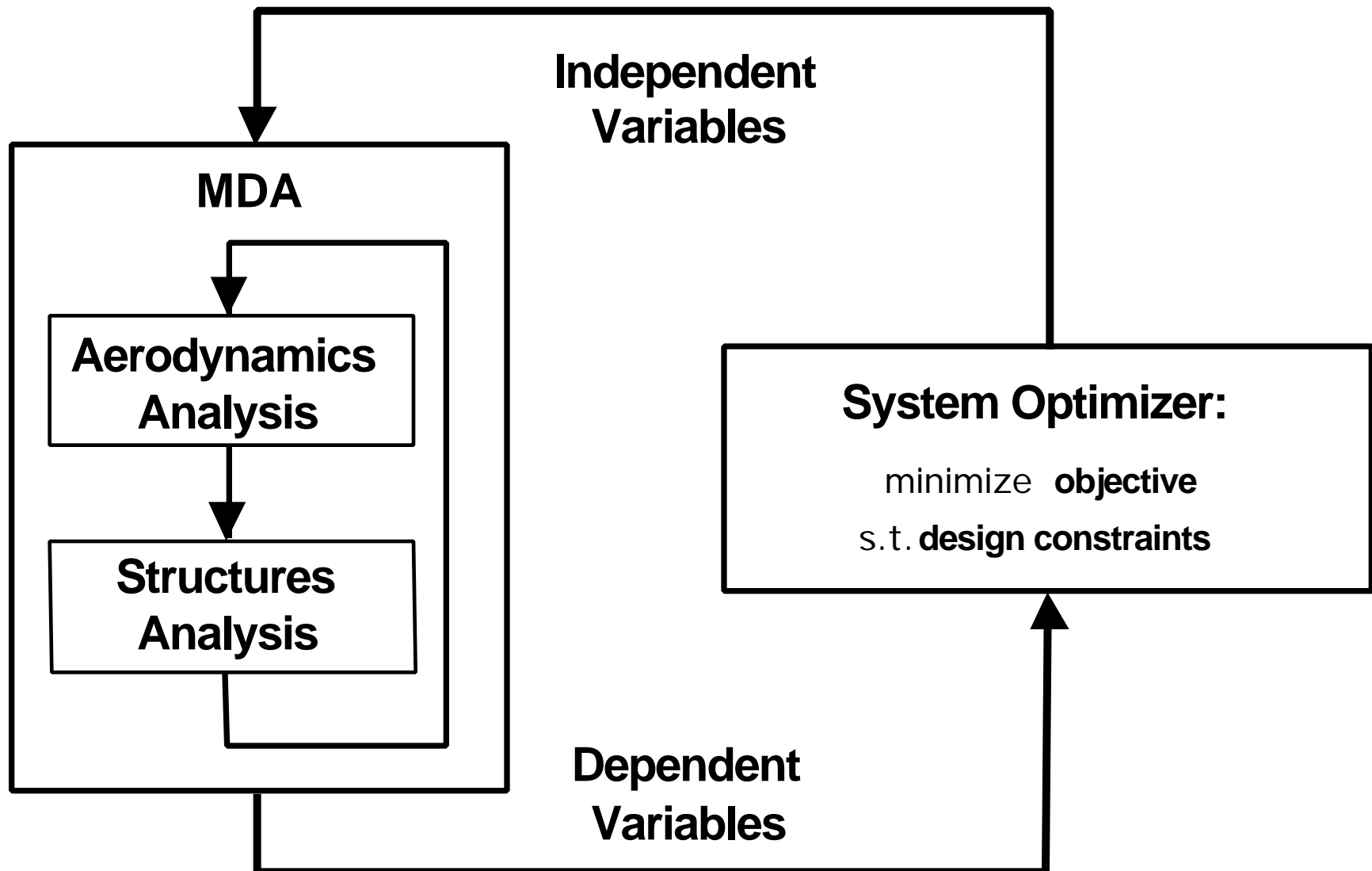
- **The goal is often “design improvement” rather than “optimization” in the rigorous sense**
- **Optimization problem definition —design variables, objectives, constraints — is an art**
- **The problem definition, including the details of the multidisciplinary analysis, usually evolves in the course of the study**

Design Problem Decomposition & Organization

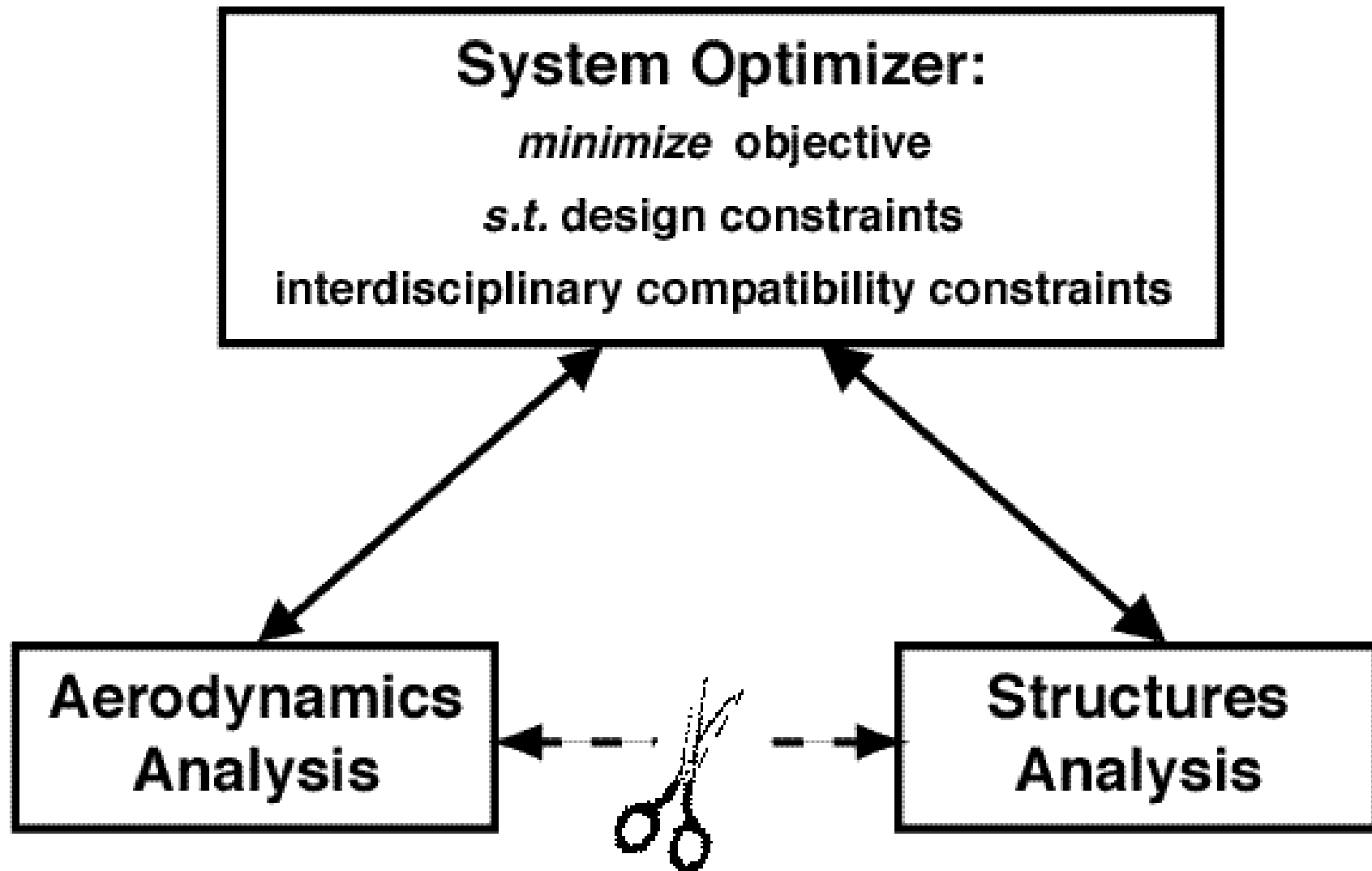
- **MDO does not consist of merely constructing a multidisciplinary analysis and wrapping an optimizer around it**
- **An MDO method consists of**
 - **an MDO formulation**
 - **a solution procedure**
- **We'll use a coupled aerodynamics-structures problem to illustrate several formulations**

Conventional Approach

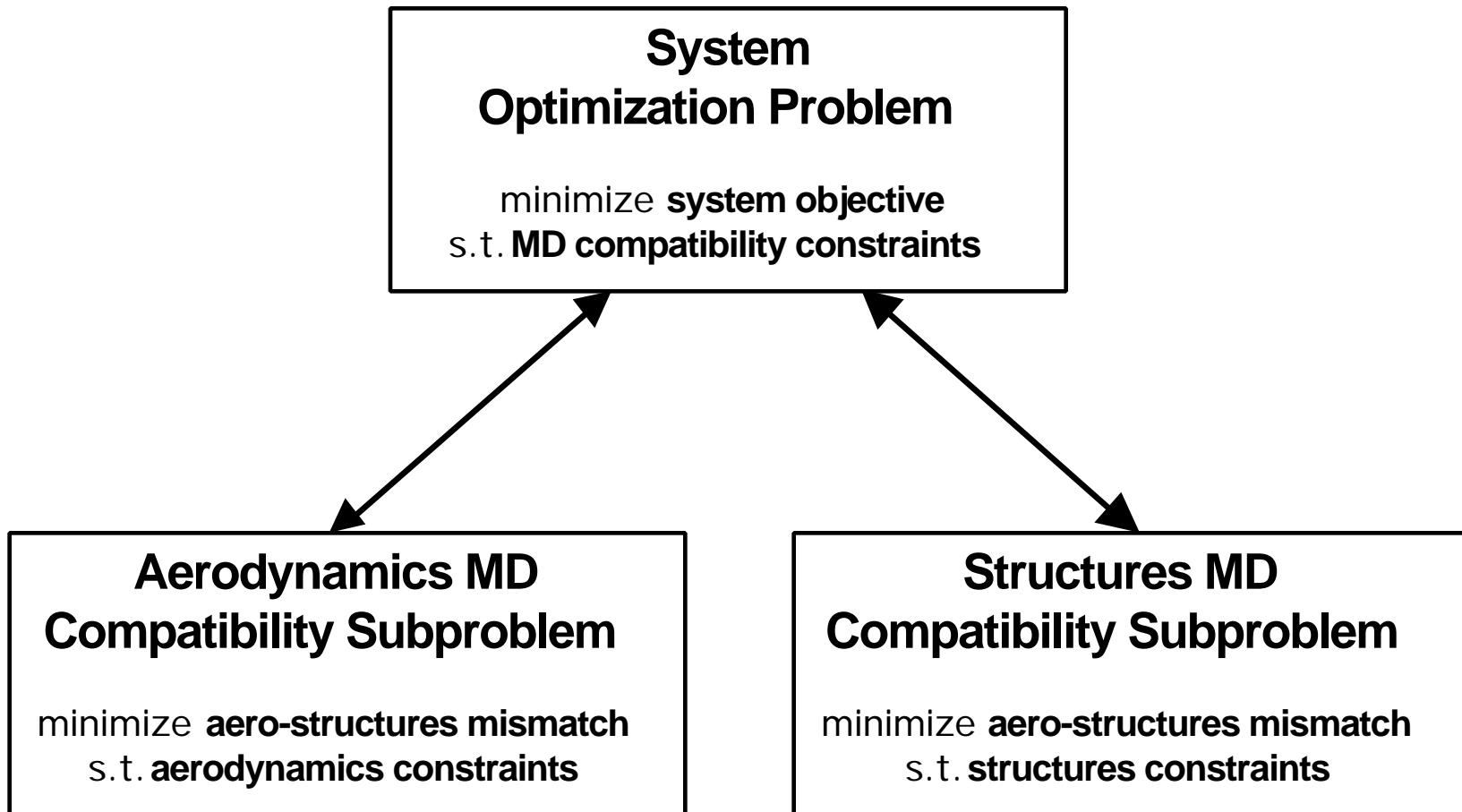
a.k.a. Multidisciplinary Feasible (MDF)



Interdisciplinary Feasible (IDF)



Collaborative Optimization



MDO Formulation Issues

- **MDO formulations remain merely candidate approaches until**
 - **proven equivalent to the MDF formulation**
 - **coupled with an effective optimization algorithm**
- **Rigorous mathematical analyses are now available for some of the formulations**
- **CO & IDF appear best suited to problems with weak, narrow interdisciplinary coupling**
- **For strong, broad interdisciplinary coupling only the MDF and a few other formulations are safe**

Optimization Procedures and Issues

- **The generalized sensitivity equations permit construction of consistent multidisciplinary sensitivities from the constituent disciplinary sensitivities**
- **Alternatives to gradient-based optimization include**
 - **pattern search methods**
 - **evolutionary algorithms (e.g., genetic algorithms)**
 - **discrete search methods**
- **There is no counterpart to the NACA 0012 airfoil or the ONERA M6 wing for testing MDO methods**
- **The MDO Branch has established the MDO Test Suite (on the WWW) for testing various MDO methods**

Management and Cultural Implementation

- **Profound cultural issues exist in conducting meaningful multidisciplinary applications in a research organization**
- **Discipline specialists want to use their latest tools, but these are rarely suitable for MDO applications**
 - long run times
 - requires expert user (not robust)
- **Problem definition should be done up front and this is very time-consuming**
- **For some of our recent studies see**
<http://fmad-www.larc.nasa.gov/mdob/MDOB/teams.index>



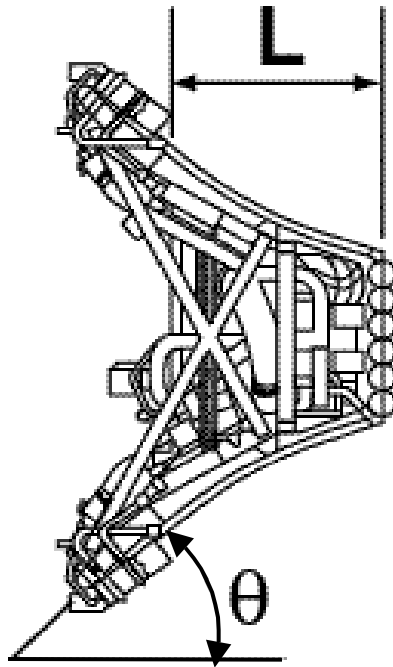
Team Dynamics

Engineering Team Performance Scale

- **Developed by Ron Nowaczyk : ICASE / Clemson University**
 - **<http://fmad-www.larc.nasa.gov/mdob/MDOB/team-dynamics/team.html>**
- **Diagnostic tool tracks the health of internal team dynamics**
- **Identifies a number of factors related to success of engineering design teams**
 - **Team Approach to the Problem or Task**
 - **Team Leadership**
 - **Coordination of Task Responsibilities**
 - **Organizational Support**
 - **Communication and Feedback**
 - **Team Roles and Norms**
 - **Your Role on the Team**
- **An intervention manual has been developed to accompany the ETPS**

Uses of Sensitivity Analysis

Optimization

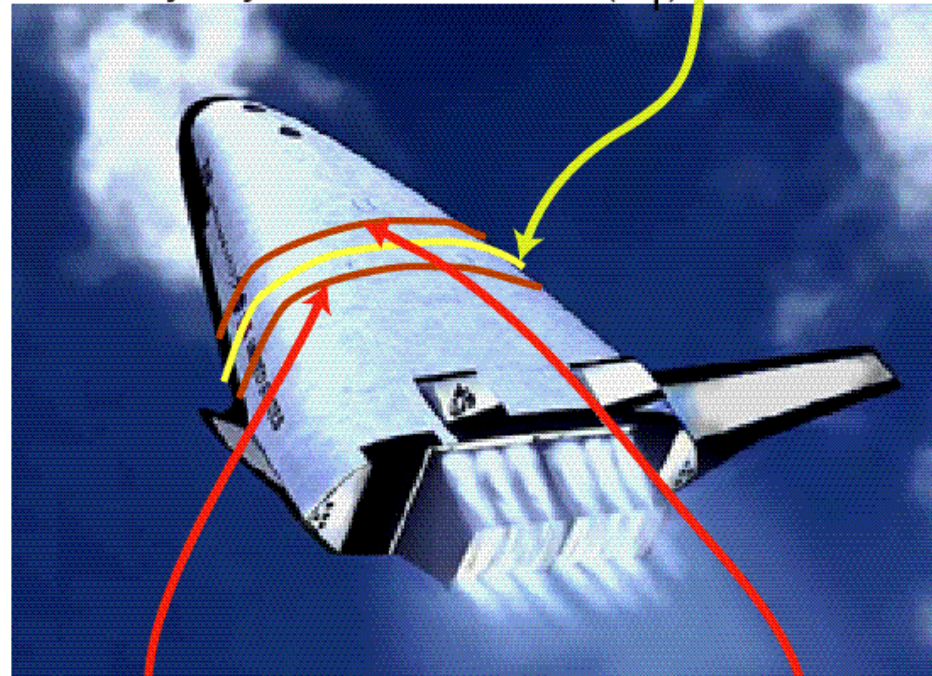


Min $G=GLOW$

$$\left[\frac{\partial G}{\partial L}, \frac{\partial G}{\partial \theta} \right]$$

Uncertainties

Boundary Layer Transition Front (X_T)



Transition Front Uncertainty Band

$$C_L = \left[\frac{\partial C_L}{\partial X_T} \right] X_T$$

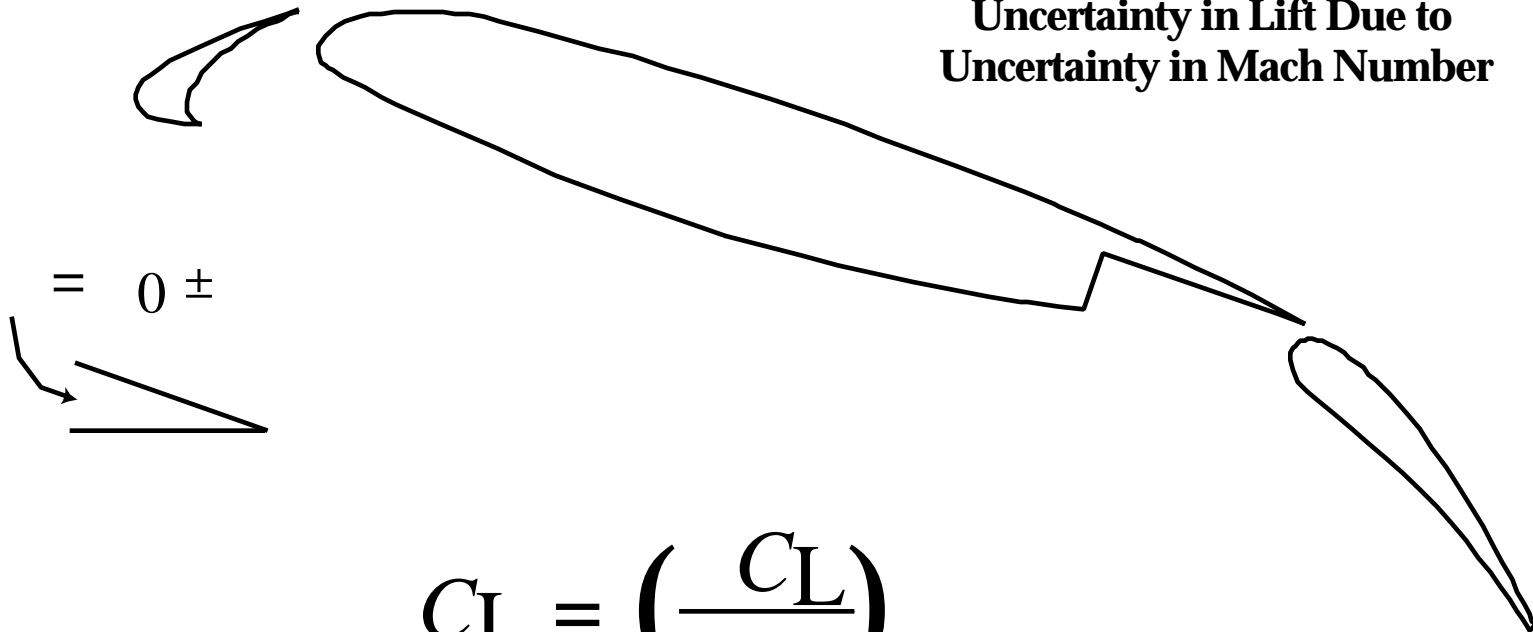
Uncertainty Analysis via Sensitivities



$$M = M_0 \pm \Delta M$$

$$C_L = \left(-\frac{C_L}{M} \right) \Delta M$$

**Uncertainty in Lift Due to
Uncertainty in Mach Number**

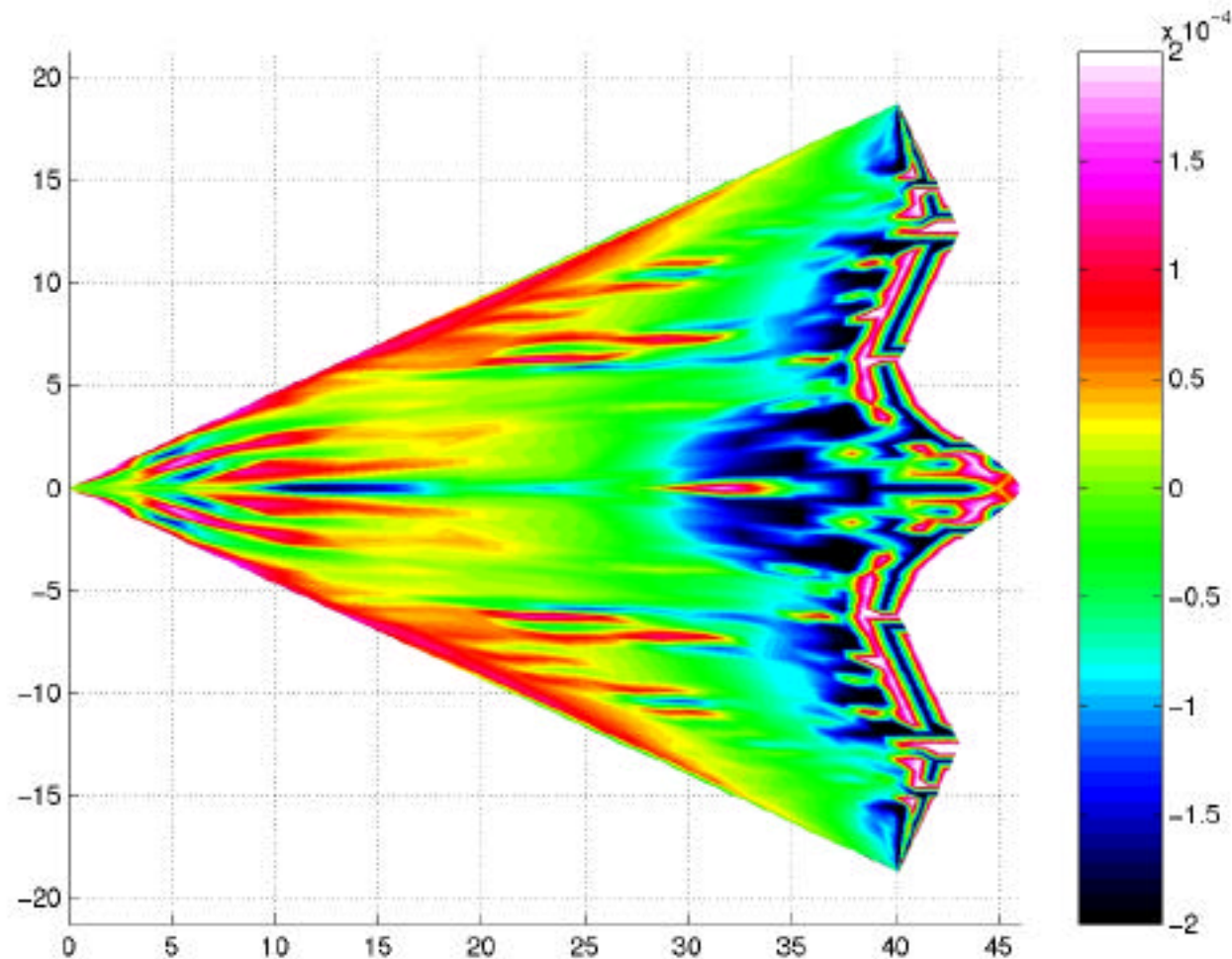


$$C_L = \left(-\frac{C_L}{\alpha} \right) \Delta \alpha$$

**Uncertainty in Lift Due to
Uncertainty in Angle of Attack**

Pitching Moment Sensitivity Due to Surface Displacement

ADJIFOR Applied to Panel Code



$$\frac{\partial C_m}{\partial X_n}$$

Optimization Under Uncertainties

- **Approaches**
 - **Reliability-based Design**
 - design to a prescribed probability of failure
 - **Robust Design**
 - design to a relatively flat optimum
- **These techniques arose in Civil Engineering and are now being investigated for aircraft engines and airframe structures**
- **These require significantly more computation than deterministic design**

Aerodynamic Approximations

- **Use of time-dependent CFD in MDO is out of the question for years to come**
- **Aerodynamic approximations are most needed for time-dependent problems**
 - **unsteady flows**
 - **aeroelasticity**
 - **aeroacoustics**
- **Reduced-order models, including proper orthogonal decompositions, are a promising candidate**

Aerodynamic Optimization

- **Adjoint methods have led to significant improvement in gradient-based optimization**
- **For many problems, inverse methods, e.g., CDISC, are still the methods of choice**
- **DACE methods, e.g., 3DOPT, are effective for problems with complex design spaces (many local minima)**
- **The MDO challenges are**
 - **retaining the efficiency of adjoint methods when CFD codes are coupled with black box codes from other disciplines**
 - **exploiting inverse methods in formulations such as IDF, CO, etc.**

Experimental Validation

- **Validation of sensitivity analysis is still done experimentally by what amounts to a finite-difference approximation**
- **Validation of optimization does not consist merely of validating the analysis at the putative optimum point**
- **The intellectual challenge is devising a new, effective approach to experimental validation of sensitivities and results of design space searches**

Requirements on Fluid Dynamics Tools for Use in MDO

- **Provide sensitivity analysis**
- **Exploit approximations as much as possible**
- **Be robust**
- **Be automated**
- **Built on parametric model descriptions**
- **Provide thorough documentation**

Key URLs

- **MDO Branch Home Page**
 - <http://fmad-www.larc.nasa.gov/mdob/MDOB/>
- **Publications**
 - [.../Publications/pub.index.html](#)
 - list of publications since 1994, with many papers available electronically
- **Conference Presentations**
 - [.../Conference/conf-present.html](#)
 - electronic copies of all conference presentations since 1997
- **Team Dynamics**
 - [.../team-dynamics/team.html](#)
 - several in-depth studies of MD teaming issues
- **MDO Test Suite**
 - [.../mdo.test/index.html](#)
 - explanations, code & sample results for MDO problems